

On the Observation of Slow Wave Processes in Deforming Rock Sample

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Abstract

The main goal of this investigation is the attempt to use the earlier developed autowave theory of plasticity to describe the rock deformation, i.e. silvinit, marble and sandstone. To visualize the localization patterns observed by mechanical testing a technique of double-exposure speckle-photography has been used. The development of localized plastic deformation has an autowave character. The autowaves resulting from the compressing process of the rock samples have propagation rates $\sim 10^{-5} \dots 10^{-4}$ m/s close to the respective values obtained for slow S-waves, which propagate in the earth's crust after earthquakes or mine shocks (0.3...3.0 km per year).

Keywords

Plastic Deformation; Localization; Speckle Photography; Autowaves; Rock

Introduction

The experimental studies of plastic flow in solids, carried out during last decades¹, allow one to throw light upon the plasticity phenomenon and to detect the most important experimental fact that the plastic flow would exhibit a localization behavior from yield point to failure. Recently strong experimental evidences for the above point of view were presented independently by the authors in². To visualize the localization patterns observed by mechanical testing a technique of double-exposure speckle-photography was used. As it is known, autowave theory is very perspective to explain the deformation phenomena in rocks. Many authorities in the field of mathematical and physical theory of plasticity acknowledge that plastic flow localization is one of the most puzzling phenomena in the modern system of views on the nature of strength and plasticity. The plastic flow development in metals and alloys has been investigated thoroughly; and the results obtained are presented in the paper². It is found that the plastic deformation is prone to localization at all the flow stages, which is manifested in the

origination of localized plasticity autowaves. Investigations were recently performed using the alkali halide crystals NaCl, KCl and LiF^{3,4} and different kinds of rock⁵; in which the results obtained support our contention that the deformation has an autowave nature.

This suggests that the deforming medium becomes spontaneously stratified into macroscopic layers, with deforming (active) layers alternating with non-deforming (passive) ones. In a general case, the boundaries between such layers are mobile; therefore, the process of plastic flow is conventionally considered as evolution of localized plastic flow patterns.

The phenomenology and quantitative characteristics of the localization effect have been fully elucidated nowadays. Thus a detailed investigation of space-time periodic localization patterns¹ allows one to refer the localization phenomenon to self-organization processes. Of great importance here is the finding that plastic flow localization patterns have apparently all the signs of autowave (self-excited) process. This comes into particular prominence at the linear deformation hardening stage where the localization of plastic flow is manifested as generation of a phase autowave having length $\lambda \approx 10^{-2}$ m and propagation rate $10^{-5} \leq V_{aw} \leq 10^{-4}$ m/s. The autowaves are distinct from the well-known plastic deformation waves arising in solids under shock loading.

At attempt is made herein to consider the problem of so-called slow motions which are termed in geophysics as S-waves⁶⁻⁹. That would originate and travel in rocks after earthquakes or mine shocks; and such waves have low propagation rates (0.3...3.0 km per year). The occurrence of S-waves and their nature have not been elucidated thus far.

By addressing such slow motions, one can certainly apply the general principles of mechanics. Thus we attempted to trace this kind of phenomena in the rock samples under compressive load and define their quantitative characteristics. There is good reason to believe that the S-waves and the localized plasticity autowaves observed in metals and alloys are closely related phenomena¹. The tests were carried out on the compressive samples of silvinit (NaCl+KCl), marble (CaCO₃) and sandstone (SiO₂). It is found that these materials deform by dislocation glide, twinning and grain-boundary sliding, respectively¹⁰.

The Experimental Method

The experimental method was developed to investigate the deformation fields. The physical basis of this method is presented in¹¹⁻¹³; and its implementation is described for the case of diffuse object in the work by J. Ohtsubo and T. Asakura¹⁴. According to these workers, the rate of any point on a diffuse object surface is given by

$$v = \frac{2w}{T} \frac{\langle I \rangle^2}{\langle I^2 \rangle - \langle I \rangle^2}, \quad (1)$$

where w is the laser beam radius; T is the measurement interval; I is the brightness at the measured point; $\langle I \rangle$ is the average intensity of the reflected light and $\sigma^2 = \langle I^2 \rangle - \langle I \rangle^2$. It is followed from the above that the rate of the point is inversely proportional to the mean-square dispersion of brightness and is directly proportional to mean brightness squared for the measured point in the time period T . An analysis of the speckle patterns observed experimentally for a diffuse scattering object suggests that the rate measured for a point on the sample surface is directly proportional to brightness dispersion in the time interval T .

A block-diagram of the experimental setup is shown in Fig. 1a. The test sample was illuminated by coherent He-Ne laser light (1); and speckle structure recording was performed for the deforming sample with the aid of a CCD camera having resolution of 1280×1024×10 bit, which was connected with a computer by a bus IEEE1394. The setup features motorized zoom (3), CCD camera (4) and laser power supply block (2). The control program of a microcontroller has been provided for the effectiveness of setup operation, i.e. changes in the illumination intensity, exposure, focus and magnification as well as stepping up/down the lens.

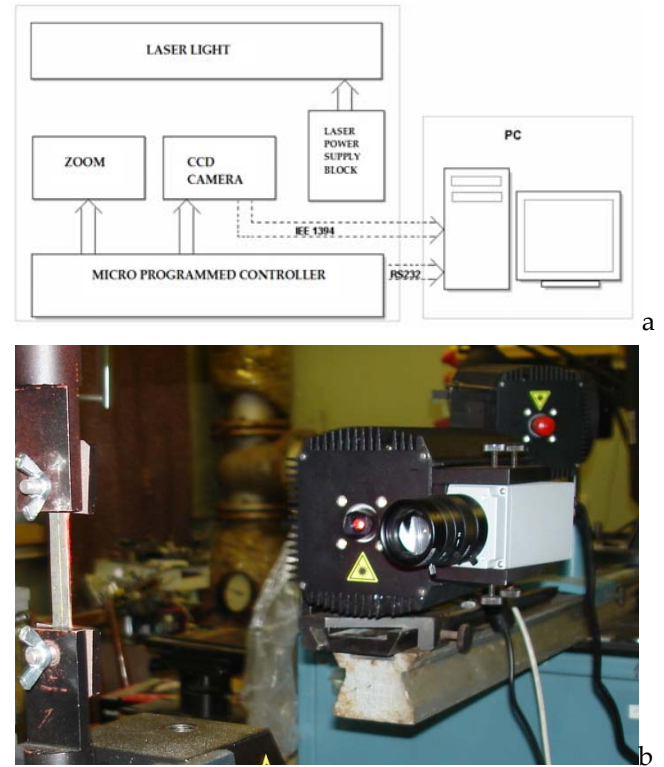


FIG. 1 THE EXPERIMENTAL SETUP:

- (A) A BLOCK-DIAGRAM OF THE EXPERIMENTAL SETUP;
(B) A COMPUTERIZED COMPLEX ALMEC-TV

In plastic deformation investigations, an analysis of first order statistics may be supplemented by the application of conventional speckle photography technique; then both sets of data on local strain fields could be matched. To this end, the opposite side of the sample placed in the clamps of the testing machine is illuminated by the coherent light and its speckle photographs are obtained as well. The decoding procedure of speckle photographs is as follows. The tilt and step of the Yung bands a determined for pre-assigned points of specklograms and displacement vector fields $\mathbf{r}(x, y)$ are calculated for the following plastic distortion tensor components, i.e. elongation, reduction, shear and rotation, respectively¹⁵:

$$\beta_{ij} = \nabla \mathbf{r}(x, y) = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} \\ \varepsilon_{yx} & \varepsilon_{yy} \end{bmatrix} + \omega_z. \quad (2)$$

Experimental Results

The test samples with dimensions 25×12×10 mm have been tested in compression in the direction of long axis x on a testing machine Instron-1185; and the mobile clamp of the testing machine has motion velocity $v_{mach} = 0.1 \dots 1.0$ m/min. The stress-strain diagrams $\sigma(\varepsilon)$ obtained for the tested rock samples are demonstrated

in Fig. 2 (a, b, c). It can be seen that the curves have segments corresponding to a sharp drop of stresses, which is an indication of sample embrittlement. Brittle fracture would occur in the test sample for the total deformation $\varepsilon_{tot} = 1.5 \dots 3.0 \%$.

Using speckle photography developed at the Institute of Strength Physics and Materials Science SB RAS and digital speckle photography technique, the strain distributions in the sample volume are examined in detail¹⁵. Macro-scale localized deformation zones are found to occur at all the flow stages in the compressive rock samples, with the rest of material volumes remaining practically undeformed. The localization fronts occurring in the deforming sample volume would move in an intricate manner.

Figure 3 illustrates the localized deformation patterns observed for the compressive samples of sandstone (a) and marble (b); in addition, the positions of deformation fronts (in the order of appearance) are denoted by dotted lines and digits. It can be observed that the deforming sample volume undergoes fragmentation, with the fragment boundaries shifting continuously.

The linear segments of the plot $\sigma(\varepsilon)$ indicate that with growing total deformation, the localized plasticity zones would travel along the sample. This kind of behavior is illustrated in Fig. 4a for the total strains of 0.5 and 0.7%, respectively. By constant-rate compressive loading, $\varepsilon_{tot} \sim t$; therefore, the co-ordinate X was determined for a localization nucleus over the entire specimen length; then the motion rate was determined for the given localization nucleus from the inclination of the plot $X-t$ (Fig. 4b). Using the same procedure, the nuclei's motion rates v_{aw} are determined for three kinds of rock; and the values obtained are listed in the Table I.

In order to assess the probable influence of loading rate v_{mach} on the propagation rate of localized plasticity nuclei v_{aw} , the engineering rate v_{mach} was increased by one order. The ratio $v_{aw} \approx 20v_{mach}$ obtained for the test samples of marble and sandstone corresponds to that of metallic materials¹.

Thus, the propagation rates of localized deformation fronts were determined for the rock samples with the aid of a computerized complex ALMEC-tv (Fig. 1b). The values obtained are in the interval of 0.9...1.3 km per year. Evidently, the latter values have the same

order of magnitude as slow motion rates. This leads to the conclusion that slow motions are localized plasticity waves which originate from rocks due to earthquakes or mine shocks.

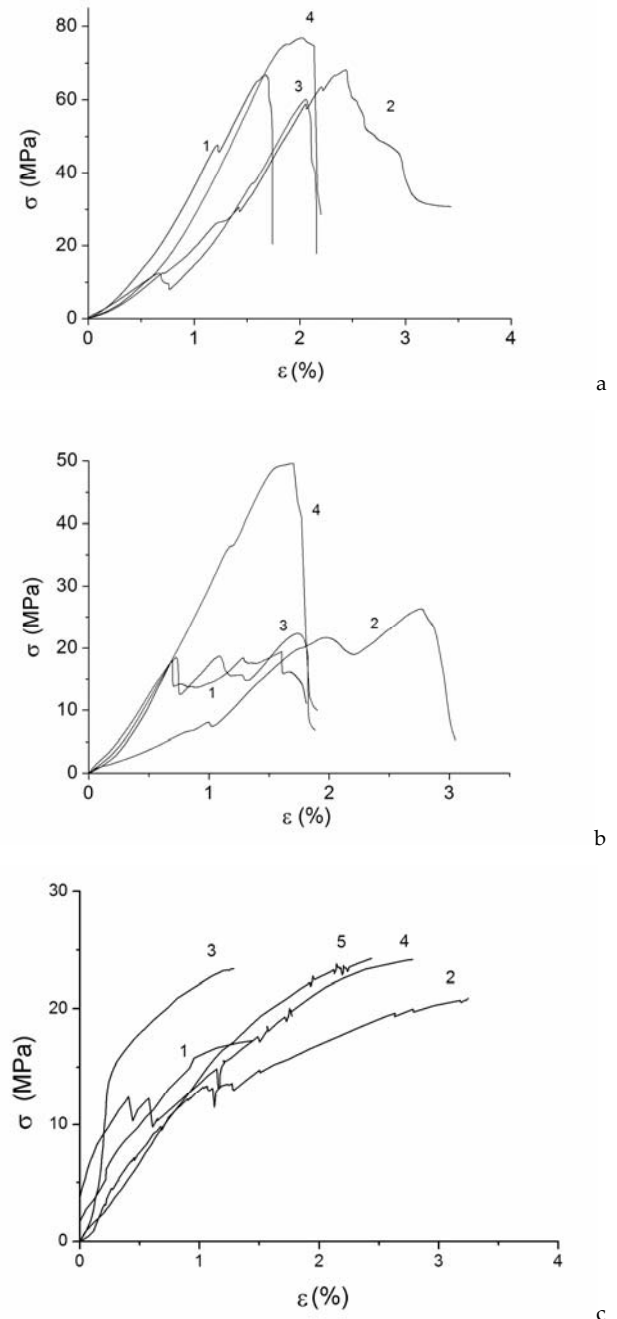


FIG.2 DEFORMATION CURVES OF ROCK SAMPLES:
(A) SANDSTONE TESTED AT COMPRESSIVE LOADING RATES OF 0.1 MM/MIN (1); 0.5 MM/MIN (2); 1.0 MM/MIN (3) AND 10.0 MM/MIN (4);
(B) MARBLE TESTED AT DIFFERENT MOTION RATES OF A MOBILE CLAMP: 0.1 MM/MIN (1); 0.5 MM/MIN (2); 1.0 MM/MIN (3) AND 10.0 MM/MIN (4);
(C) SILVINITE SAMPLES TESTED AT A COMPRESSIVE LOADING RATE OF 0.1 MM/MIN.

Consider another argument in favor of the above conclusion. On the base of experimental data on plastic localization in metals¹, we derived an elastic-plastic deformation invariant of the form

$$\lambda \cdot V_{aw} = \frac{1}{2} d \cdot V_t' \quad (3)$$

where λ is the separation between mobile flow nuclei (wavelength); V_{aw} is the nuclei's motion rate; d is the interplanar distance, which corresponds to the X-ray reflex intensity¹⁶, and V_t is the rate of elastic transverse waves propagating in a solid¹⁷.

Let us see if relation (3) holds good for the investigated rocks. For the sake of convenience, it is possible to be rewritten (3) as

$$\frac{\lambda \cdot V_{aw}}{d \cdot V_t} \approx \frac{1}{2}. \quad (4)$$

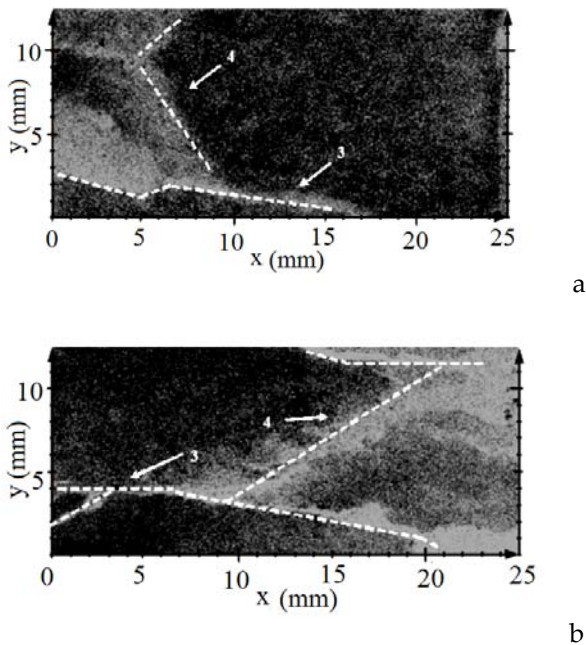


FIG. 3 MOTION OF LOCALIZED DEFORMATION ZONES;
(A) MARBLE SAMPLE: TOTAL DEFORMATION $\varepsilon_{tot} = 1.7\%$;
COMPRESSIVE LOADING RATE $V_{MACH} = 0.5$ MM/MIN;
(B) SANDSTONE SAMPLE: TOTAL DEFORMATION $\varepsilon_{tot} = 1.7\%$;
COMPRESSIVE LOADING RATE $V_{MACH} = 0.1$ MM/MIN.

The estimates were made using the values listed in the which Table experimental data on λ and V_{aw} as well as the literature values d and V_t reported in^{16, 17}. The faithfulness of the numerical estimates is open to question since controversial V_t data is reported for different rocks; moreover, in the case of rocks, the accuracy of experimental λ and V_{aw} data is less

satisfactory relative to that of metals¹. Nonetheless, the ratios $\lambda \cdot V_{aw} / d \cdot V_t$ listed in the Table I are close to $\frac{1}{2}$ (4).

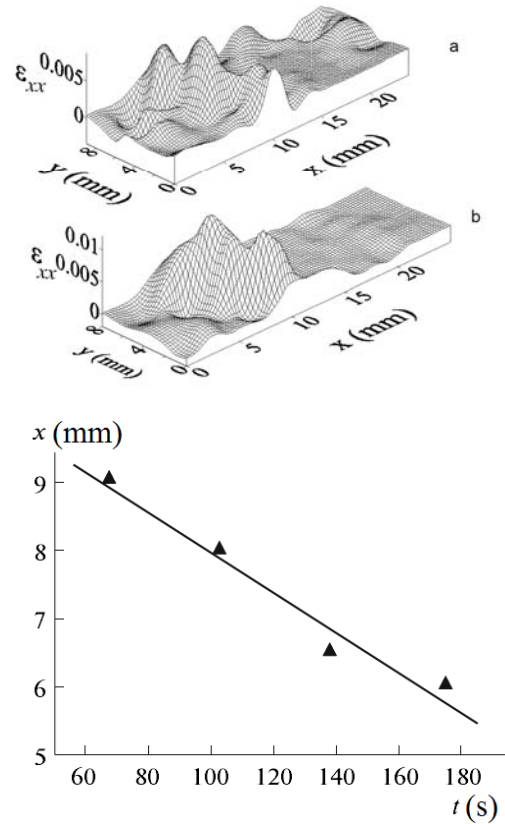


FIG. 4 DEFORMATION LOCALIZATION IN SILVINITES;
DISTRIBUTIONS OF COMPONENT $\varepsilon_{xx}(x, y)$ AS WAVE
PATTERNS FOR THE TOTAL DEFORMATION $\varepsilon_{tot} = 0.5\%$ (A)
AND $\varepsilon_{tot} = 0.7\%$ (B); LOCAL ELONGATION (ε_{xx}) MAXIMA X
PLOTTED ALONG THE MIDDLE PORTION OF THE SILVINITES
SAMPLE AGAINST THE TIME OF COMPRESSIVE LOADING (C)

TABLE 1 DATA FOR CALCULATION USING EQ. (4)

Characteristic	Rock Type		
	Silvinites	Marble	Sandstone
λ , mm	10	4	4
V_{aw} , m/s	$2.8 \cdot 10^{-5}$	$4.2 \cdot 10^{-5}$	$3.0 \cdot 10^{-5}$
d , nm ¹⁵	0.3	0.386	0.41
V_t , m/s ¹⁶		1905	1860
$\lambda \cdot V_{aw} / d \cdot V_t$		0.22...0.28	0.15...0.19

The Nature of Macro-Scale Localization of Deformation

Recent experimental evidence suggests that the localization of plastic deformation can take several forms and plays an important role in all the flow stages from yield point to failure¹⁸. Therefore, the

various forms of deformation localization, which are observable in between the onset of yielding and material fracture, call for classification.

When a specimen is tested in tension at a constant rate of crosshead motion, the plastic deformation evolves non-uniformly with time and localizes in space. In accordance with Haken¹⁹, this phenomenon should be regarded as a process of self-organization. The latter concept is being widely used in the modern physics of plasticity. At the beginning of the discussion of the wave phenomena related to the plastic deformation, we have to recollect that according to Haken¹⁹ self-organization is the acquisition by a system of spatial, temporal or functional inhomogeneity without any specific action from the outside. Evidently, this definition is completely applicable to the waves of localized plastic deformation discussed here. Certainly, the physical cause of these self-organization processes can be very complicated; and probably the only way to success is the use of analogy between autowaves and macroscopic spatial-time structures observed, for example, in some chemical systems²⁰.

It has been shown previously^{21,22} that a general approach to the problem of self-organization in open systems should be based on an analysis and solution of parabolic differential equations in partial derivatives of the following type

$$\dot{Y} = \varphi(Y) + DY'', \quad (5)$$

where Y is a certain variable characterizing the kinetics of the processes occurring in the system, $\varphi(Y)$, and the so-called "point kinetics", i.e. non-linear function describing the rate of Y variation in a local microvolume and a transport coefficient, D , has, apparently, dimensionality of the diffusion coefficient. It is of importance that the (5) contains first derivative in time, which makes it appropriate for the description of irreversible processes.

It is well known that two equations similar to (5) are necessary for full description of self-organization processes in an open system. They have to describe the evolution rate of two factors which play the opposite roles of activator (autocatalisator) and inhibitor (damping). The choice of factors usable for these goals is not a simple task.

When the problem of plasticity is considered in the context of synergetic approach, it is imperative that physically meaningful parameters be used, which is appropriate for the description of a deforming system.

Nicolis and Prigogine²¹ first proposed that by addressing plastic flow, deformation, ε , used as autocatalytic factor and stresses, σ , as damping factor.

In the frames of this approach, one can deduce differential equations, which describe the evolution of strain and stress in the course of plastic deformation of solids. Bearing in the mind that the deforming medium during plastic flow is a mosaic of regions differing in the magnitude of deformation, and it is believed that the strain $\varepsilon = \varepsilon(x, y, z, t)$. Therefore using the equation of plastic flow continuity, one can write

$$\dot{\varepsilon} = \nabla \cdot (D_\varepsilon \nabla \varepsilon). \quad (6)$$

Here $D_\varepsilon \nabla \varepsilon$ is the flow of deformation in the field of deformation gradient $\nabla \varepsilon$, the coefficient $D_\varepsilon = D_\varepsilon(x, y, z)$ and ∇ is the "nabla" operator. For a one-dimensional case, (6) yields

$$\dot{\varepsilon} = \varepsilon D'_\varepsilon + D_\varepsilon \varepsilon'' = f(\varepsilon, \sigma) + D_\varepsilon \varepsilon'', \quad (7)$$

where $f(\varepsilon, \sigma) = \varepsilon D'_\varepsilon$ is the non-linear function of strain and stress. The point should be made that the application of similar relations to the plastic flow description has been developed by Aifantis as gradient theory of plasticity²².

In addition to the mosaic of stressed regions, stress concentrators of various scales also emerge in a loaded specimen. However, the equation describing the relaxation rate of stresses $\dot{\sigma}$ cannot be derived from the respective equation of continuity due to the fact that on the regions' boundaries a jump-wise change occurs in the internal stresses. To derive the equation for $\dot{\sigma}$, assume $\dot{\sigma} = \dot{\sigma}_e + \dot{\sigma}_v$, with $\dot{\sigma}_e$ and $\dot{\sigma}_v$ being the relaxation rates of elastic and viscous stresses, respectively. It is supposed that $\dot{\sigma}_e$ is a nonlinear function of stress and strain, i. e. $\dot{\sigma}_e = g(\sigma, \varepsilon)$. The magnitude of viscous stresses, σ_v , is related to the variation in the propagation rate of elastic wave in the course of the deformation by the well-known relationship

$$\sigma_v = \eta \nabla^2 V_s. \quad (8)$$

Here $\nabla \cdot \nabla \equiv \nabla^2 \equiv \Delta$ is the Laplacian; and trivial transformation of (8) yields

$$\dot{\sigma}_v = V_s \nabla \cdot (\eta \nabla V_s) = V_s \eta \Delta V_s. \quad (9)$$

As reported by Zuev and Semukhin²³, the sound velocity (elastic waves), V_s , depends linearly on

acting stresses $V_s = V^{**} \pm \xi \sigma$; $V^{**} = \text{const}$. Correspondingly, $\Delta V_s = \xi \sigma''$ and the differential equation describing the rate of relaxation of stresses assume the form

$$\dot{\sigma} = \dot{\sigma}_e + \eta \xi V_s \Delta \sigma = g(\sigma, \varepsilon) + D_\sigma \sigma'', \quad (10)$$

where the coefficient $D_\sigma = \eta \xi V_s$ has also the dimensionality of the diffusion coefficient. A set of (7) and (10) is appropriate for the description of deforming system evolution.

In fact, the set of (7) and (10) describes the evolution of mosaic field of strains and stresses existing in the loaded specimens. The suggestion is reasonable that the nonlinear functions (points kinetics) $f(\varepsilon, \sigma)$ and $g(\varepsilon, \sigma)$ describe strains and stresses corresponding to some accommodation modes of deformation, which are initiated by contact interaction between the elementary shears. On the contrary, the diffusion-like terms in (7) and (10) take into account "overshoot" of strains and stresses to the crystal regions placed far away from the acting shears. The appearance of these terms makes easier the nucleation of new local deformation domains in the fore of the plastic deformation front. It has to be reminded here that this "overshoot" is not related to the great path of dislocations: new shears are originated far from the acting domain of plasticity.

A model of plastic deformation development is proposed in¹ and elaborated in¹⁸. In the framework of this model, the origination of localized plasticity autowaves in a deforming solid is addressed. The model proposed herein is based on invariant (5), which is an indirect evidence for the active role the phonon subsystem of the crystal plays in the formation of localized plasticity autowave patterns. This is easily explained due to the fact that the only contribution to the rate of macroscopic plastic deformation $\dot{\varepsilon} = b \rho_d V_d$ is that of dislocations overcoming the local barriers²⁴, i.e. $V_d \neq 0$, with the motion rate of dislocations being controlled by the interaction with the phonon and electron gases²⁵ whose state would affect both the micro- and the macro-scale plastic flow dynamics.

In the proposed model, however, the phonon subsystem plays a more significant role in the development of localized plastic flow in solids. Indeed, the plastic deformation involves two kinds of interrelated events occurring concurrently in the

deforming medium (i) relaxation acts which are due to the jump-wise motion of individual dislocations or dislocation ensembles or due to the propagation of localized plastic flow autowaves and (ii) acoustic emission pulses which in point of fact are elastic waves generated by each relaxation event. A conventional approach to plasticity description is based on the use of acoustic emission signals for studying the kinetics of shears and for structural integrity monitoring. As a matter of fact, the above effects are traditionally examined independently since the retroaction of acoustic emission pulses on material plasticity is generally taken to be negligible.

However, the physical aspect of the problem considered herein consists in the fact that a unified account is sought for two closely interrelated categories of events. Indeed, an elementary plasticity act (shear) is capable of generating an acoustic impulse, which, in turn, is likely to initiate a new shear. Thus we have to account for the causal link between the two kinds of interrelated events occurring simultaneously in the deforming medium: (i) dislocation shears which cause relaxation of stresses, and (ii) acoustic emission pulses which generate the redistribution of stresses. In the framework of this approach, the idea of spontaneous layering was formulated in²⁶ to address a system undergoing self-organization. As a result of layering, two interrelated subsystems, i.e. informative and dynamic one, would form. For the case of deforming medium, an appropriate choice of subsystems appears to be sufficiently simple, i.e. the role of information signals which would cause relaxation of shears, is assigned to acoustic emission pulses (phonons) generated by other, similar shears. As a result, redistribution of the elastic field takes place to initiate new shears in the dynamic dislocation subsystem.

Thus, one of the assumptions of the proposed model is that the leading role in the development of localized plastic flow is assigned to acoustic emission impulses. The implications of this for the effectuality of the model underlie what follows. The well-known Wallner effect, i.e. the appearance of lines on the surface of brittle cleavage, has been examined. It was found that the lines would appear due to the propagating crack trajectories curving under the impact of acoustic impulses which are generated, in turn, by the growing cracks. Assuming that the energy is only spent for increasing the area of the cleavage surface, ΔS , the lower limit of energy required for

curving the crack trajectory was estimated from the experimental data reported in²⁷. The grooves occurring on the cleavage surface had depth $\sim 1 \mu\text{m}$; the sample diameter was $\sim 10^{-2} \text{ m}$ and the area of the cleavage surface $\Delta S \approx 10^{-8} \text{ m}^2$. The characteristic surface energy density for metals, $\gamma \approx 1 \text{ J/m}^2$; hence the amount of energy expended for curving a growing crack trajectory is calculated as $\Delta W \geq \gamma \Delta S \approx 10^{-8} \text{ J} \approx 6.25 \cdot 10^{11} \text{ eV}$, which appears sufficient to activate for new elementary plasticity acts.

The connection between the acoustic and mechanical properties of the deforming medium is explicitly formulated in terms of reciprocal action of defects on the acoustic characteristics of the crystal. The ultrasound rate is shown²³ to depend nonlinearly on the strain and the flow stress. Thus for the linear work hardening stage, the ultrasound rate would have a constant value, which would decrease for the parabolic work hardening stage to increase again upon transition to the prefailure stage.

Further light has been shed on one of the principal assumptions of the proposed model, i.e. the important role of acoustic impulses in localized plasticity development. Thus the correspondence between localized deformation nuclei and acoustic emission sources was validated experimentally²³. The tests were carried out using material whose deformation involves the Lüders front propagation. It was found that the localized plasticity nuclei emergent in the deforming sample would serve as sources of acoustic emission impulses.

The main assumption of the model¹⁸ is that the deforming medium would acquire certain properties of an active medium which possesses energy storage located at the stress concentrators. The same definition is thought to be applied to slow motions^{6,8} since the earthquake center serves as energy source for S-waves. It is thus believed that the motion of localized plasticity nuclei is analogous to slow motions occurring in rocks⁸.

Conclusions

Thus it is established that the features of plastic flow and fracture in rocks are similar to that in metals. It allows one to use the autowave theory of plasticity for explanation of deformation processes of various rocks.

The patterns of plastic flow localization in solids and their comparison to the data on deformation

mechanisms allow us to determine some features of the process, among which the most important are as follows.

- (i) The localization phenomena occur spontaneously at a constant velocity of sample tension and do not require a special action for their appearance.
- (ii) Localization patterns gradually and regularly change as plastic flow is developed, and their evolution is closely related to the flow stages.
- (iii) At certain stages, localization patterns exhibit pronounced spatial and temporal periodicity.
- (iv) Each localization pattern and phenomenon at a corresponding stage of the flow process are associated with certain microscopic mechanisms of strain hardening occurring at this stage.
- (v) The defect structure of a material and its strain hardening irreversibly change during plastic deformation so that the deformed medium is explicitly nonlinear.

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Authorship: over 400 papers, 4 monographs, 9 patents. The most important publication: L.B. Zuev, "The linear work hardening stage and de Broglie equation for autowaves of localized plasticity" *Int. J. Sol. Str.*, vol. 42, pp. 943-949, 2005. Research interests: strength and plasticity physics; physics of crystal defects; materials science.



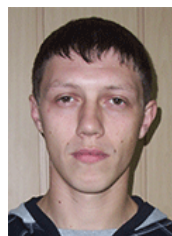
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The most important publication: L.B. Zuev, V.I. Danilov, S.A. Barannikova, "Plastic flow, necking and failure in metals, alloys and ceramics," *Mater. Sci. and Eng. A*, v. 483-484, pp. 223-227, 2008. Research interests: condensed-state physics, material science, deformed-solid mechanics and crystallography.



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The most important publication: L.B. Zuev, S.N. Polyakov, V.V. Gorbatenko, "Instrumentation for speckle interferometry and techniques for investigating deformation and fracture" *Proc. of SPIE*, vol. 4900, Part 2, pp. 1197-1208, 2002. Research interests: computerized methods for calculation and analysis of plastic deformation fields.



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The most important publication: S.A. Barannikova, M.V. Nadezhkin, L.B. Zuev, V.M. Zhigalkin, "On inhomogeneous straining in compressed sylvinites," *Tech. Phys. Lett.*, vol. 36, pp. 507-510, 2010. Research interests: Investigations into the nature of macro-inhomogeneity, localization and self-organization of plastic flow and fracture in alkaline-halide crystals and rocks.